Simulation of cyclic loading tests on geosynthetic reinforcement

Kongkitkul, W.¹, Hirakawa, D.², Tatsuoka, F.³, and Uchimura, T.⁴

In the design procedure of geosynthetic reinforced-soil structures, the residual deformation during the service period of the structure is one of the key issues. To investigate the development of residual strain of polymer reinforcements, a series of load-controlled tensile tests was performed generating the following loading histories: a) continuous monotonic loading (ML) at a constant load rate; b) creep (or sustained) loading; and c) cyclic loading with controlled amplitudes and frequencies. Though it has been usually considered that residual straining during cyclic loading is due to the effects of time-independent cyclic loading history (i.e., as a function of the number of loading cycles; amplitude; and so on), it was found from this study that cyclic residual straining is due essentially to the loading rate effects caused by material viscous property. A non-linear three-component model originally developed for simulating the rate-dependent deformation of geomaterials (i.e., soils; and rocks) was modified to simulate the relationship between tensile load and strain for ML; creep; cyclic loading; and general loading histories obtained from the present study.

Keywords: geogrid, cyclic, viscous, residual deformation, simulation

1. Introduction
Polymer geosynthetic reinforcement is widely used to reinforce backfill for soil structures, such as sloped embankments; retaining walls and bridge abutments. Such a popular use as above is due to a high cost-effectiveness and a high stability, in particular against high seismic loads due to its flexibility and ductility. However, geosynthetic-reinforced soil (GRS) structures could be relatively more deformable, exhibiting larger long-term residual deformation, when compared with soil structures reinforced with metal strips. In the ordinary design procedure, therefore, it is specified that the design rupture strength of polymer reinforcement decreases with an increase in the specified design life of structure. On the other hand, there has been a very limited report on the failure of GRS structure due to the creep rupture failure of polymer reinforcement under usual service load conditions. Furthermore, the laboratory tensile tests of polymer geogrid reinforcement (Kongkitkul et al., 2002a) showed that the strength under the same loading conditions does not decrease by creep, cyclic and other loading histories applied before rupture. It seems therefore that the current design procedure is not relevant in this respect.

Despite its paramount importance in the design of permanent GRS structures, the residual deformation of GRS structures could be predicted confidently only when the residual deformation characteristics of both geosynthetic reinforcement and backfill are well understood. To this end, the tensile load and strain behaviour together with residual deformation characteristics of polymer geosynthetic reinforcement have been studied by many researchers (e.g., Bathurst and Cai, 1994; Min et al., 1995; Leshchinsky et al., 1997; Moraci & Montanelli, 1997; Ling et al., 1998). However, most of these researches focused separately on the behaviours under monotonic, creep and cyclic loading conditions. So, possible correlations among the deformations taking place by monotonic, creep and cyclic loading histories and other general loading histories have not been obtained.

The following two factors may develop residual strains under cyclic loading conditions in geosynthetic reinforcement:
1) Loading rate effects caused by material viscous properties: The residual strains developed by this factor during cyclic loading should be independent from the number of loading cycles applied for a given total period of cyclic loading.
2) Rate-independent effects of cyclic loading history: The residual strains developed by this factor during cyclic loading should be a function of rate-independent cyclic loading conditions, such as cyclic load amplitude, initial loading level, the number of loading cycles and so on, while independent of loading frequency for a given number of loading cycles.

However, Kongkitkul et al. (2002a) showed that the creep deformation of geosynthetic reinforcement is a viscous response of the material and the development of residual strain during cyclic loading is also due to the viscous property of reinforcement.

In the present study, a series of load-controlled cyclic and creep loading tests were conducted during otherwise monotonic tensile loading at a constant load rate on two types of polymer geogrid (the same ones as used by
Kongkitkul et al., 2002b). The test results were analysed to show that the development of residual strain during cyclic loading is due to the viscous property of reinforcement. The test results were also simulated by the non-linear three-component model not taking into account the rate-independent effects of cyclic loading history (i.e., the number of loading cycles and others) on the model parameters (Di Benedetto et al., 2002; Tatsuoka et al., 2002).

Table 1. Physical properties of geogrids used in this study.

<table>
<thead>
<tr>
<th>Geogrid's name</th>
<th>Vectran</th>
<th>Vinylon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre material: longitudinal transverse</td>
<td>Polyarylate Polyester</td>
<td>Polyvinyl alcohol PVC</td>
</tr>
<tr>
<td>Coating material</td>
<td>PVC</td>
<td>Polyvinyl alcohol</td>
</tr>
<tr>
<td>$V_{\text{max, nominal}}$ (kN/m)*</td>
<td>88.0</td>
<td>60.8</td>
</tr>
</tbody>
</table>

Note: * is the value provided by the respective manufacturer.

Table 2. Number of cycles per cyclic loading stage and loading rates (corresponding to different loading frequencies for a loading period of 30 minutes per stage).

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>No. of cycles/stage</th>
<th>Loading rate during cyclic loading (kN/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>18</td>
<td>± 12</td>
</tr>
<tr>
<td>0.02</td>
<td>36</td>
<td>± 24</td>
</tr>
<tr>
<td>0.05</td>
<td>90</td>
<td>± 60</td>
</tr>
<tr>
<td>0.1</td>
<td>180</td>
<td>± 120</td>
</tr>
<tr>
<td>0.2</td>
<td>360</td>
<td>± 240</td>
</tr>
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</table>

Figure 1. a) a specimen attached with laser displacement transducers; and b) schematic diagram of the load-controlled tensile loading apparatus.

2. Test materials

The properties of the two types of geogrid used in this study are summarized in Table 1. The core materials in the machine direction are Polyarylate and Polyvinyl alcohol for Vectran and Vinylon geogrids. The specimens were virgin that had been store in a clean and temperature-controlled room to avoid any chemical reaction and UV light. Each specimen consisted of three longitudinal strands with a whole length before wrapped around the gripping device equal to about 900 mm. The length of the unconfined part of the specimen wrapped around the gripping device is 240 mm. A pair of laser displacement transducers was attached on the specimen to locally measure tensile strains (Fig. 1a).

3. Test apparatus and loading patterns

In order to control the frequency and amplitude in the respective cyclic loading test, a pneumatic loading system consisting of a double-action air-cylinder, an electro-pneumatic (EP) transducer and an air-booster was used (Fig. 1b). The loading rate during loading and unloading was controlled by adjusting the pressure inside the lower room of air-cylinder controlled by using the EP. The air-booster was used to achieve a better response of the pneumatic loading system when reversing the loading direction and changing the loading rate.

The gripping device consisted of a pair of roller clamps having a groove to fasten the specimen inside with a small steel rod. To avoid any slippage of the specimen from the surface of the clamp, a sheet of sand paper was firmly glued on the middle area, where the specimen was wrapped around, of each clamp.

The loading scheme was set up assuming as if all the specimens were installed in the same structure subjected to monotonic loading at a specified loading rate during the construction process and subsequently cyclic loading that is added during service. In other tests, creep loading...
tests were performed. The following patterns of loading histories were generated:
1) Monotonic loading (ML) at a load rate of 60 kN/m/min continuously up to a specified ultimate load, which is slightly lower than the tensile rupture strength at this load rate of each type of reinforcement so that an abrupt tensile failure can be avoided and the laser displacement transducers could be removed safely.

Figure 3. Tensile load-strain relationships from ML tests with and without cyclic loading at \( f = 0.01 \) & 0.2 Hz: a) Vectran; and b) Vinylon

Figure 4. Time-histories of residual strain accumulating at the base loads from cyclic loading at \( f = 0.01 - 0.2 \) Hz: a) Vectran; and b) Vinylon
2) Cyclic loading (CL) for a period 30 minutes at different load rates corresponding to different frequencies \( f \) for a load amplitude of 10 kN/m, applied during otherwise ML at a rate of 60 kN/m/min (Fig. 2a). The generated frequencies were equal to 0.01; 0.02; 0.05; 0.1 and 0.2 Hz. The same load rate, equal to 60 kN/m/min, was used for ML loading up to a specified load level where cyclic loading was added continuously from the previous ML. This cyclic loading method was to simulate additional loads by traffic applied on GRS structures. The CL histories were applied at either two or three stages depending on the rupture strength of each type of reinforcement. The number of loading cycles \( N_c \) and the loading rate at each stage were determined so that the total period of CL became 30 minutes (Table 2).

3) Creep loading for a period of 30 minutes at the maximum and minimum loads at the respective cyclic loading stage (Fig. 2b).

4. Test results and discussion

4.1 Cyclic deformation characteristics

The relationships between tensile load, \( V \), and strain, \( \varepsilon \), from the tests with CL histories at \( f = 0.01 \& 0.2 \) Hz are presented in Figs. 3a & 3b for Vectran and Vinylon geogrids, respectively. The \( V - \varepsilon \) relations from continuous ML tests (dash curves) were also plotted in those figures. The origin of cyclic residual strain was defined at the start of respective CL history when the tensile load was equal to the base load (when the cyclic load was zero). Thus, this kind of residual deformation corresponds to those observed at the moment when the temporary traffic loads are not acting on GRS structures. The time histories of cyclic residual strain, defined as above, of Vectran and Vinylon geogrids were presented in Figs. 4a & 4b. The following trends of behaviour may be seen from these figures:

1) The \( V - \varepsilon \) curve after the restart of ML following each CL stage tended to rejoin the one obtained from the corresponding continuous ML test without the intermission of CL stages. That is, the effects of residual strain by CL disappeared when the load became sufficiently high load level.

2) The residual strain increment per cycle was largest during the first cycle. This was due to the occurrence of large irreversible strain increment when the load level exceeded the previous maximum value during the first half cycle.

3) The time histories of residual strain are rather similar for different loading frequencies, \( f \), in a range of 0.01 – 0.2 Hz under otherwise the same loading conditions for both types of geogrid. This result indicates that the development of residual strain during CL is a viscous response of the polymer geogrid.

4) All the time histories are asymptotic to the respective upper bound and the pattern is the same for different loading frequencies. This trend of behaviour is essentially the same as creep strain. It is seen from the above that the nature of cyclic residual strain is very similar to creep strain.

5) The amount of developed residual strain decreases with an increase in the load level, which is due to an increase in the tangent stiffness of the \( V - \varepsilon \) relation with an increase in the load level.

![Figure 5](image-url) Figure 5. Relationship between residual tensile strains at an elapsed time equal to 1,000 seconds and at a number of cycles equal to 10 from cyclic loading tests at different loading frequencies and load levels.

Fig. 5 shows the relationship between the residual tensile strain at an elapsed time equal to 1,000 seconds, \((\Delta \varepsilon)_{t=1,000s}\), and the one at a number of loading cycles equal to 10, \((\Delta \varepsilon)_{N_c=10}\), at different frequencies and load levels for both types of geogrid. It can be seen that the values of \((\Delta \varepsilon)_{t=1,000s}\) for the different frequencies at the same load level are essentially the same. On the other hand, the value of \((\Delta \varepsilon)_{N_c=10}\) decreases with an increase in the loading frequency (i.e., with a decrease in the elapsed time at the end of ten loading cycles). This plot confirms that the development of residual tensile strain during cyclic loading history is essentially a viscous response, but rate-independent cyclic loading effects are negligible, if any.

4.2 Creep deformation characteristics

Figs. 6a & 6b, respectively, compares the \( V - \varepsilon \) relations from a continuous ML test and two or three other ML tests with creep loading at multiple intermediate stages (lasting 30 minutes at each) for the two types of geogrid. The results from simulation based on the three-component model also presented in these will be explained later. It may be seen that, upon the restart of ML at a constant load rate (60 kN/m/min) after a creep loading stage, the \( V - \varepsilon \) relation showed a high tangent stiffness compared with the one observed at the same load level during continuous ML. This trend of behaviour is similar to the case of cyclic loading test. Subsequently, the \( V - \varepsilon \) relation tended to rejoin the original curve observed during continuous ML when the tensile load became sufficiently higher than the creep load level. This result obviously shows that creep
deformation is not a degradation phenomenon while it is just a viscous response of geosynthetic reinforcement.

5. Non-linear three-component model

Structure of the model: Kongkitkul et al. (2002a) and Hirakawa et al. (2003) showed that the non-linear three-component model originally developed for geomaterials (Fig. 7) can simulate very well the $V - \varepsilon$ relations during ML at different strain rates, ML with stepwise change in strain rate and creep loading. The stress $\sigma$ in the model could be replaced by the tensile load per unit width of reinforcement $V$. Then, the tensile load $V$ can be expressed in the ML case as:

$$V = V' (\varepsilon'') + V''$$

where $V' (\varepsilon'')$ is the inviscid load component, which is a unique function of irreversible tensile strain $\varepsilon''$; and $V''$ is the viscous load component, which is either a unique function of instantaneous irreversible tensile strain $\varepsilon''$ and its rate $\dot{\varepsilon}''$ (the isotach viscosity) or a function of not only the instantaneous values of $\varepsilon''$ and $\dot{\varepsilon}''$ and the previous loading history (the TESRA viscosity). The isotach viscosity is relevant to the two types of geogrid used in the present study.

Reference load-strain relation during ML: The rate-independent $V' - \varepsilon''$ relation, called the reference relation, for the respective type of geosynthetic reinforcement was fitted by the following polynomial equation:

$$V' = f(\varepsilon'') = \sum_{i=1}^{m} a_i (\varepsilon'')^{i-1}$$

where $a_i$ is the coefficient for term $i$.

Viscous component for ML: The tensile load jump $\Delta V$ observed upon a stepwise change in the strain rate is always proportional to the instantaneous value of $V$ (Hirakawa et al., 2003). This fact indicates that the viscous tensile load can be expressed as:

$$V'' = g(\varepsilon'', \dot{\varepsilon}'')$$

where $g(\varepsilon'', \dot{\varepsilon}'')$ is a non-linear function of $\dot{\varepsilon}''$, called the viscosity function, which is always positive whether $\dot{\varepsilon}''$ is positive or negative and given as follows (Di Benedetto et al. 2002; Tatsuoka et al. 2002):

$$g(\varepsilon'', \dot{\varepsilon}'') = \alpha \cdot \{1 - \exp[1 - (\dot{\varepsilon}'')]^m\} \geq 0$$

where $|\dot{\varepsilon}''|$ is the absolute value of $\dot{\varepsilon}''$; and $\alpha$, $m$ and $\varepsilon''$ are the material constants.

Reference load-strain relation during CL: Due to the shape of load-strain curves during unloading/reloading is largely different from the one during the primary loading curve for the two types of geogrid used in the present study, it becomes necessary to introduce imaginary primary loading and unloading curves, $V' = g(\varepsilon'')$ (with positive values of $\varepsilon''$) and $V' = -g(-\varepsilon'')$ (with negative values of $\varepsilon''$), that have a shape similar to the shape of...
the actual unloading and reloading curves, but different from the actual primary loading curve, \( V' = f(e^m) \), as illustrated in Fig. 8. Hysteretic curves during cyclic loading are obtained by shifting these imaginary primary loading and unloading curves without scaling. A polynomial function was also employed for \( V' = g(e^m) \) and it was determined to best fit the inferred inviscid tensile load-reversible strain curves (at zero-reversible strain rate) during unloading and reloading. The hysteretic load-strain relations during CL were obtained as follows referring to Fig. 8:

1) During the first primary loading from origin \( o \) \((e_o^m = 0, V_o^m = 0)\) until point \( a \), the load-strain relation follows the primary loading curve, \( V' = f(e^m) \).

2) Assume that loading direction is reversed at point \( a \). The unloading curve, bound for point \( b \), is obtained by using the known imaginary primary unloading curve, \( V' = -g(-e^m) \), and the coordinate at point \( a \), \((e^m_a, V^m_a)\), as:

\[
(V' - V^m_a) = -g\left[-(e^m - e^m_a)\right]
\]

where \((V^m_a - V^m_b)/(V^m_c - V^m_d) = (e^m_a - e^m_c)/(e^m_b - e^m_d) = 1.0\).

3) When the loading is reversed to reloading at point \( b \), the reloading (with positive \( d e^m \)), bound for the latest previous reversing point before point \( b \) (i.e., point \( a \)), is obtained by shifting the imaginary primary loading curve as:

\[
(V' - V^m_b) = g(e^m - e^m_b) \]

where \((V^m_b - V^m_c)/(V^m_c - V^m_a) = (e^m_b - e^m_c)/(e^m_b - e^m_a) = 1.0\).

where point \( d \) \((e^m_d, V^m_d)\) is the intersection of the straight line from the origin \( o \) which is parallel to the straight line between points \( b \) and \( a \) with the imaginary primary loading curve \( V' = g(e^m) \). The reloading curve does rejoin the actual primary loading curve, \( V' = f(e^m) \) at point \( a \), but it is not smoothly.

Viscous component for CL: The viscous component during cyclic loading, \( V^* \), is positive during reloading (with positive \( d e^m \)) and negative during unloading (with negative \( d e^m \)) as it is natural to assume that \( V' \) is zero at the start of unloading, reloading and so on, it was assumed that \( V^* \) during CL is obtained as:

\[
V^* (e^*, e^m, h) = V^* - g (e^*)
\]

where \( V^* \) is the inviscid load component used only to obtain \( V^* \) during CL and is obtained as:

1) For \( V^* \) at point \( b \) during unloading (Fig. 9a), \( V^* \) is the value of \( V' \) at point \( b^* \) along the imaginary primary unloading curve that corresponds to point \( b \) as:

\[
V^* = V^m_a - V^m_c \quad (\geq 0)
\]

2) For \( V^* \) at point \( d \) during reloading (Fig. 9b), \( V^* \) is the value of \( V' \) at point \( d^* \) along the imaginary primary loading curve that corresponds to point \( d \) as:

\[
V^* = \frac{V'^d - V'^b}{V'^a - V'^c} \quad (\geq 0)
\]

Note that the value of \( V^* \) when reloading curve rejoins the actual primary loading curve \( V' = f(e^m) \) at point \( a \) is scaled up so that it is equal to \( V' \) before the unloading starts. Therefore, the total load (inviscid + viscous) from reloading curve smoothly continues the primary loading curve at point \( a \) without any sudden dropping in the viscous component.

6. Simulation

The parameters of viscosity function, \( g(e^m) \), used in the present simulation, which are the same as those determined by Hirakawa et al. (2003), are listed in Table 3. These parameters were determined to fit the loading rate effects on the load-strain relation observed when changing stepwise the strain rate, as explained in Hirakawa et al. (2003). In Figs. 6a & 6b, the measured \( V - e \) relations are compared with their simulations. Fig. 10 compares the measured creep residual strains at an elapsed time equal to 1,000 seconds and those simulated by the model for all the creep tests performed in the present study. It may be seen from Figs. 6 & 10 that the proposed model is able to simulate very well both the entire load-strain-time relations from the load-controlled tests with and without multiple-stages of creep loading including the amount of creep strain.
Table 3. Viscosity parameters used in the simulation

<table>
<thead>
<tr>
<th>Viscosity parameters</th>
<th>Vectran</th>
<th>Vinylon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.44</td>
<td>0.76</td>
</tr>
<tr>
<td>$m$</td>
<td>0.09</td>
<td>0.12</td>
</tr>
<tr>
<td>$(\frac{\text{d}e}{\text{d}t})_e$ (%/sec)</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

Fig. 10. Comparison of the predicted and measured creep residual strains at an elapsed time equal to 1,000 seconds

Fig. 11. Simulation of cyclic loading tests presented in Figs. 3a-1 and 3b-1: a) Vectran; and b) Vinylon

Figs. 11a & 11b compare the measured and simulated $V - \varepsilon$ relations obtained from load-controlled ML with multiple CL stages at $f = 0.01$ Hz. The model parameters used in these simulation are the same as those used to simulate continuous ML tests and creep tests (Table 3).

Fig. 12 compares the measured cyclic residual strains from all the cyclic loading tests lasting for a period of 1,000 seconds and those simulated by the proposed model. It may be seen from Figs. 11 & 12 that the model can simulate rather accurately the whole viscous effects on the load-strain behaviour observed during not only ML and creep loading but also CL for both types of geogrid. It should be noted that any rate-independent effects of cyclic loading is not taken into account in this simulation. Some inconsistency may be seen between the measured results and the simulated ones, which were obtained by using the same model parameters under different test conditions for the same type of geogrid. This is due mostly to an inevitable scatter in the material properties among different specimens.

Fig. 12. Comparison of the predicted and measured cyclic residual strains at an elapsed time equal to 1,000 seconds

7. Conclusions
The following conclusions could be derived from the results of experiment and simulation shown in this paper:

1) Upon the start of reloading at a constant load rate after a creep or cyclic loading stage, the load-strain relation exhibited a very high tangent stiffness and subsequently tended to rejoin the original one that could be obtained by continuous monotonic loading at the same load rate. Consequently, the effects of previous creep or cyclic loading disappeared after the load became higher than certain level. This fact indicates that creep deformation as well as residual strain development during cyclic loading are not degradation phenomena.

2) The rate-independent effects of cyclic loading were negligible while the residual strains developing during cyclic loading were due essentially to the material viscous properties.

3) The load-strain-time behaviour observed during monotonic, creep, and cyclic loading could be simulated very well by the three-component model using the irreversible strain rate as the basic variable while not taking into account the rate-independent cyclic loading effects on the model parameters.
8. Acknowledgement

This study is supported by the Japan Society for the Promotion of Science through the grant: "Advanced applications of soil reinforcement technology to highly-earthquake-resistant reinforcement of existing soil structures and construction of highly-earthquake resistant and environment-friendly soil structures".

9. References


Joinsen-Seittikus no seisanji saigai shikai no shimonerehon


近年での地盤工学の重要な議論の一つに、供用期間内に土構造物に生じる残留変形を見積もること、があげられる。本研究では、a)単調載荷試験、b)荷重保持載荷試験、c)荷重振幅と周波数を制御した繰返し載荷試験、を行い、高分子補強材の荷重保持載荷・繰返し載荷時の残留変形特性を検討した。一般的に繰返し載荷によって生じる高分子補強材の残留変形は、繰返し載荷回数や振幅等の載荷履歴(時間的に依存しない変形要因)の効果と考えられてきた。しかし、本研究による検討によると、繰返し載荷による残留変形はほぼ材料粘性による載荷速度効果であることが分かった。すなわち、繰返し載荷による残留変形は、ほぼクリープ変形による時間依存変形である。

さらに、本研究では時間依存変形特性を表現するために提案された非線形レオロジーモデルを用いることにより、繰返し載荷や荷重保持を含む載荷条件での高分子補強材の変形特性をシミュレーションすることが出来た。